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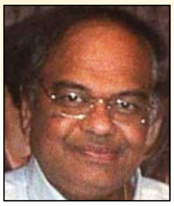
Shrinkage modeling for recycled aggregate concretes

Modelagem da retração por secagem de concretos produzidos com agregados reciclados



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Abstract

Concerns with conservation of nonrenewable resources are propelling academic research regarding the use of recycled aggregates in concrete production. Concrete's shrinkage is a phenomenon intimately linked to concrete loss of water, which is almost inevitable, since the majority of concrete structures is exposed to an environment where atmospheric humidity is below saturation condition. This paper presents an experimental study where concretes were produced varying water/cement ratio (from 0.4 to 0.8) and type and proportion of construction & demolition waste (concrete, cement, and red ceramic) used as coarse and fine recycled aggregates. Mathematical models correlating such variables with concrete's shrinkage at 56 and 224 days of age were built. The results indicate that, for the age of 56 days, the data presented excessive variability, revealing only 4 of the 7 tested variables as significant. For the age of 224 days, the proposed model still presented considerable variability, however all tested variables were detected as significant. Results point out that substitution of natural aggregates by recycled aggregates increases shrinkage, being this effect stronger when substitution comprises fine aggregates. The most pronounced effect was associated to the use of recycled concrete fine aggregate. The slightest effect was observed using recycled concrete coarse aggregate.

Keywords: *recycled aggregate concrete, shrinkage, multiple regression.*

Resumo

A preocupação com a conservação dos recursos não renováveis tem levado o meio acadêmico a pesquisar sobre a utilização dos agregados reciclados na produção de concretos. A retração por secagem do concreto é um fenômeno que está intimamente ligado à perda de água da massa do concreto, a qual é quase inevitável, desde que o concreto esteja exposto a um ambiente de umidade abaixo da condição de saturação. Este artigo apresenta um estudo experimental, onde foram produzidos concretos variando-se a relação água/cimento (de 0,4 a 0,8) e o tipo e a proporção dos três principais constituintes do resíduo de construção e demolição (concreto, argamassa e cerâmica vermelha) usados como agregados graúdos e miúdos reciclados, produzindo-se modelos matemáticos que correlacionam tais variáveis com a retração por secagem dos concretos aos 56 e 224 dias de idade. Os resultados apontam que, para a idade de 56 dias, o modelo apresentou uma excessiva variabilidade, manifestando somente 4 das 7 variáveis como termos significativos. Para a idade de 224 dias, o modelo proposto ainda apresentou uma elevada variabilidade, entretanto todas as variáveis foram tidas como significativas. Os resultados apontam que a substituição do agregado natural pelo reciclado propicia um acréscimo na retração por secagem, sendo este efeito mais sentido para a substituição do agregado miúdo. O efeito mais pronunciado está associado ao emprego do agregado miúdo reciclado de concreto e o menor, ao do agregado graúdo reciclado de concreto.

Palavras-chave: *concreto com agregados reciclados, retração por secagem, regressão múltipla.*

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1. Introduction

The use of aggregates made from recycling of construction and demolition wastes (CDW) is observed in many countries, including Brazil. The largest application of this type of recycled aggregate has been in paving layers; however its use in concrete production is increasing. An example of CDW use in concrete production comes from Germany, where the feasibility of using concrete made with recycled aggregates (recycled concrete) in structural functions has been demonstrated. This country already released Standards for the use of recycled concrete, such as DIN 4226-100 and DIN 1045-2 [1, 2].

The authors already published studies on the mechanical characteristics of concretes with different types and content of recycled aggregates, comprising properties such as compressive strength [3] and elastic modulus [4], however literature about shrinkage is scarce. Shrinkage is one of the most important concrete properties, since it is one of the main causes of cracking, assuming major relevance in analysis concerning concrete's durability, mainly when reinforced concrete is used.

Concrete's shrinkage is an inevitable phenomenon, since most concrete structures is exposed to atmospheric humidity below saturation condition. As a rule, all concrete structure will present some level of shrinkage during his life-cycle.

Grading, maximum dimension, form and superficial texture of the aggregates are factors that influence concrete's shrinkage. However, aggregate's elastic modulus is considered the most important factor [5]. Several researches [6, 7, 8] demonstrated that recycled aggregates have characteristics different from natural aggregates, as higher absorption of water, lower specific density and bulk density, among others. These differences influence directly the shrinkage of recycled concretes.

It is reasonable that recycled concrete presents larger shrinkage, since recycled aggregates have smaller elastic modulus than natural aggregates, being therefore more deformable. Besides, due to higher water absorption, recycled aggregates demand higher contents of water to obtain adequate mixture properties [9].

On the other hand, the variability of CDW composition is a restrictive factor for its large scale use. In Brazil, on the average, 65% of discarded materials are from mineral origin, 13% from wood, 8% from plastics, and 14% from other materials [10]. It is also considered that mortar, concrete and brick ceramic together correspond to more than 60% of total CDW generated [11]. Thus, the use of recycled aggregates of different compositions will turn into concretes with different mechanical characteristics and durability.

Several authors [12, 13, 14] found that shrinkage of concretes made with recycled concrete aggregate may be twice as large as shrinkage of conventional concretes. Other authors [15] found that concretes produced with recycled aggregates of mortar also present higher shrinkage than conventional concretes. It is difficult to esteem the shrinkage of concretes made with recycled aggregates of brick ceramic, since it depends on a large number of factors. However, some authors [16] estimate shrinkage in this type of concrete as 20 to 60% higher than the one observed for conventional concretes.

Shrinkage is a phenomenon that is intimately linked to the loss of water of concrete mass. It is well-known that the more water presented in the mass, the larger will be the possibility of retractions. Thus, it is possible to associate recycled aggregate concrete shrinkage with type of recycled aggregate. The more porous the recycled aggregate is, less it will restrict shrinkage, allowing larger concrete deformation. The replacement of natural aggregates by recycled aggregates influences concrete performance. So, it is necessary to understand the behavior of concretes produced with CDW.

2. Objectives

The aim of this study is modeling shrinkage behavior of concretes made with water/cement ratio between 0.4 and 0.8, produced by substituting natural aggregates by recycled aggregates, of concrete, mortar, and red ceramic, which are three main components of Brazilian CDW.

3. Methodology

3.1 Experimental project

Seven independent variables (factors) were identified, they are: proportion of fine and coarse recycled aggregate of red ceramic, proportion of fine and coarse recycled aggregate of mortar, proportion of fine and coarse recycled aggregate of concrete, and water/cement ratio. The experimental project chosen to study the effect of all factors on shrinkage was a second order composite design (SOCD). The structure of the SOCD used comprised a 2^{7-2} fractional factorial combined with 2k vertexes and central points [17].

The use of fractional factorials designs are recommended when there are a large number of factors to be investigated over one or more response variables and the goal is time and cost optimization. Fractioning means to divide the entire project in two or more blocks and then test only one of these blocks randomly [18]. This type of study supported by statistical methods has been previously performed by numerous Brazilian and international research [6, 7, 19]. The complete 2^k factorial was divided into 4 blocks, testing only one block, meaning 32 mixtures, which are mixtures 1 to 32 in Table 1.

As the experiment has 7 factors, the star has 14 vertexes, which correspond to mixtures 33 to 46. Mixtures 47 and 48 correspond to the central points. Mixtures 49 and 50 were inserted into the experimental project, since they represent the condition where all aggregates (recycled and natural) are present in the concrete mass. Table 1 shows all concrete mixtures tested in the experimental study.

The response variable (dependent variable) was the shrinkage of produced concretes, in agreement with the procedures described in *ASTM C 157-93 – Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete.* Data were collected in predefined ages (1, 4, 7, 14, 28, 56, 112, and 224 days) and a pre-humidification of the recycled aggregates was conducted, so that they would not absorb mix water, avoiding a possible modification in water/cement ratio (w/c).

Water absorption of recycled fine aggregates and natural fine aggregate was measured by the method proposed in NM 30/00 – Absorption of fine aggregate. Water absorption of recycled coarse aggregates and the natural aggregate was measured by the method proposed in NM 53/02 –Coarse aggregate – Determination of specific gravity, apparent specific gravity and water absorption.

Table 1 – Concrete mixtures defined by the second order composite design

Mix	w/c Ratio	Coarse Aggregate				Fine Aggregate			
		Natural	Concrete	Red Ceramic	Mortar	Natural	Concrete	Red Ceramic	Mortar
01	0.46	100%	0%	0%	0%	100%	0%	0%	0%
02	0.74	100%	0%	0%	0%	0%	0%	100%	0%
03	0.74	100%	0%	0%	0%	0%	100%	0%	0%
04	0.46	100%	0%	0%	0%	0%	50%	50%	0%
05	0.74	0%	0%	0%	100%	0%	0%	0%	100%
06	0.46	0%	0%	0%	100%	0%	0%	50%	50%
07	0.46	0%	0%	0%	100%	0%	50%	0%	50%
08	0.74	0%	0%	0%	100%	0%	33%	33%	33%
09	0.46	0%	0%	100%	0%	0%	0%	0%	100%
10	0.74	0%	0%	100%	0%	0%	0%	50%	50%
11	0.74	0%	0%	100%	0%	0%	50%	0%	50%
12	0.46	0%	0%	100%	0%	0%	33%	33%	33%
13	0.74	0%	0%	50%	50%	100%	0%	0%	0%
14	0.46	0%	0%	50%	50%	0%	0%	100%	0%
15	0.46	0%	0%	50%	50%	0%	100%	0%	0%
16	0.74	0%	0%	50%	50%	0%	50%	50%	0%
17	0.46	0%	100%	0%	0%	0%	0%	0%	100%
18	0.74	0%	100%	0%	0%	0%	0%	50%	50%
19	0.74	0%	100%	0%	0%	0%	50%	0%	50%
20	0.46	0%	100%	0%	0%	0%	33%	33%	33%
21	0.74	0%	50%	0%	50%	100%	0%	0%	0%
22	0.46	0%	50%	0%	50%	0%	0%	100%	0%
23	0.46	0%	50%	0%	50%	0%	100%	0%	0%
24	0.74	0%	50%	0%	50%	0%	50%	50%	0%
25	0.46	0%	50%	50%	0%	100%	0%	0%	0%
26	0.74	0%	50%	50%	0%	0%	0%	100%	0%
27	0.74	0%	50%	50%	0%	0%	100%	0%	0%
28	0.46	0%	50%	50%	0%	0%	50%	50%	0%
29	0.74	0%	33%	33%	33%	0%	0%	0%	100%
30	0.46	0%	33%	33%	33%	0%	0%	50%	50%
31	0.46	0%	33%	33%	33%	0%	50%	0%	50%
32	0.74	0%	33%	33%	33%	0%	33%	33%	33%
33	0.60	0%	50%	25%	25%	0%	33%	33%	33%
34	0.60	0%	0%	50%	50%	0%	33%	33%	33%
35	0.60	0%	25%	50%	25%	0%	33%	33%	33%
36	0.60	0%	50%	0%	50%	0%	33%	33%	33%
37	0.60	0%	25%	25%	50%	0%	33%	33%	33%
38	0.60	0%	50%	50%	0%	0%	33%	33%	33%
39	0.60	0%	33%	33%	33%	0%	50%	25%	25%
40	0.60	0%	33%	33%	33%	0%	0%	50%	50%
41	0.60	0%	33%	33%	33%	0%	25%	50%	25%
42	0.60	0%	33%	33%	33%	0%	50%	0%	50%
43	0.60	0%	33%	33%	33%	0%	25%	25%	50%
44	0.60	0%	33%	33%	33%	0%	50%	50%	0%
45	0.80	0%	33%	33%	33%	0%	33%	33%	33%
46	0.40	0%	33%	33%	33%	0%	33%	33%	33%
47	0.60	0%	33%	33%	33%	0%	33%	33%	33%
48	0.60	0%	33%	33%	33%	0%	33%	33%	33%
49	0.46	25%	25%	25%	25%	25%	25%	25%	25%
50	0.74	25%	25%	25%	25%	25%	25%	25%	25%

Table 2 – Fine aggregates characteristics

Aggregate	NM 30/00 Absorption (%)	NBR 9776/87 Specific gravity	NM 45/00 Bulk density (g/cm^3)
	Testing method		
Natural fine	0.42	2.64	1.56
Recycled fine of concrete	7.55	2.56	1.43
Recycled fine of mortar	4.13	2.60	1.39
Recycled fine of red ceramic	10.69	2.35	1.26

For each type of aggregate, water absorption was defined twice, through two samples. Average results for fine aggregates are in Table 2 and for coarse aggregates are in Table 3.

Specific gravity for recycled and natural aggregates were also determined by the method proposed in NBR 9776/87 – Fine aggregate – Determination of specific gravity by Chapman Flask for the fine aggregates and by NM 53/02 – Coarse aggregate – Determination of apparent specific gravity and water absorption for the coarse aggregates. For each type of aggregate, specific gravity was determined twice, through two samples. Average results for fine aggregates are in Table 2 and for coarse aggregates are in Table 3.

Bulk density of recycled and natural aggregates was determined by the method proposed in NM 45/00 – Aggregates – Determination of bulk density and empty voids. For each type of aggregate, bulk density was determined twice using two samples. The objective of bulk density determination was to discover which employed aggregates generated better packing, providing better distribution and leaving smaller gaps in a determined volume. Since recycled aggregates come from different raw-materials, with different specific gravities, results cannot be directly compared, because the influence of specific gravity was not isolated. Thus, the best way to compare them was to parameterize them considering the specific gravity of the natural aggregate in its group (coarse and fine) and thereby determining the refined bulk density of such materials. Average bulk density for fine aggregates is seen in Table 2 and for coarse aggregates in Table 3.

3.2 Concrete production

An experimental dosage was performed with the natural aggregates using IPT/EPUSP method [20], fixing workability through the slump test method in 12±2cm, and determining the dosage diagram (Figure 1). Table 4 shows the concrete composition for w/c ratio equal to 0.46, performed with natural aggregates. When substituting natural aggregates for recycled ones, some adjustments were necessary in concrete dosage, such as volume compensation and adding water from the pre-soaking of recycled aggregates.

Firstly, a volume compensation of the recycled aggregates to be employed in the pre-determined mixtures was performed, seeing that simple mass substitution of the natural recycled aggregate would result in higher volumes of recycled aggregates, since specific gravity of recycled aggregates is lower than specific gravity of natural aggregates. This requires more water and cement in order to produce equivalent mixtures of the reference mixtures (those with natural aggregates) [6, 7, 15, 21]. Volume compensation for recycled aggregates in the experimental project mixtures was carried out according to Equation 1, where:

M_{RA}= recycled aggregate mass (kg)
M_{NA}= natural aggregate mass (kg)
γ_{RA}= specific gravity of recycled aggregate
γ_{NA}= specific gravity of natural aggregate

Table 3 – Coarse aggregates characteristics

Aggregate	NM 53/02 Absorption (%)	NM 53/02 Specific gravity	NM 45/00 Bulk density (g/cm^3)
	Testing method		
Natural coarse	1.22	2.87	1.44
Recycled coarse of concrete	5.65	2.27	1.54
Recycled coarse of mortar	9.52	2.01	1.44
Recycled coarse of red ceramic	15.62	1.86	1.46

$$M_{RA} = M_{NA} \cdot \frac{\gamma_{RA}}{\gamma_{NA}} \quad (1)$$

Afterwards, it was determined the water mass to be added to the recycled aggregates before producing the concretes. So, the aggregates were put already soaked in the concrete mixer, avoiding that part of mixing water could be absorbed by the aggregates, which would hinder the hydrating process.

This pre-soaked water initially absorbed by the recycled aggregates will then be available within the mixture, hydrating the non-hydrated cement particles, helping in the curing process. The water in the aggregate also promotes a favorable transition zone between the new paste and the recycled aggregate, with some cases where it is impossible to define a distinct limit between the two phases, even by means of a microscope [22].

Some authors [6, 7] used proportions of 40% to 50% of total water to be absorbed in 24 hours. Others [23, 24, 25], used higher water proportions in the pre-soaking, reaching saturation. In this work, recycled aggregates were moistened 10 minutes prior to mixing, with 80% of the water estimated to be absorbed in 24 hours by the corresponding recycled aggregate. This value was employed because it was observed that during water absorption tests of the recycled aggregates these aggregates reach an average of 80% of total water absorption in the first 120 minutes after mixing. Since the hydrating reactions last a long time, surpassing cement's grip time [5], which in the case of the cement used, was 245 minutes, it means that up to this time, water is available for hydrating reactions without being absorbed by the aggregates.

After this pre-soaking procedure, all coarse aggregates were added to a vertical axis pan-mixer, along with part of the mixing water. Afterwards, cement and the rest of mixing water were added, mixing them for four minutes. Then, fine aggregate was added and it was mixed for four additional minutes. In some mixes it was also necessary to add some superplasticizer, until the mass reached the de-

Figure 1 – Diagram of concrete dosage

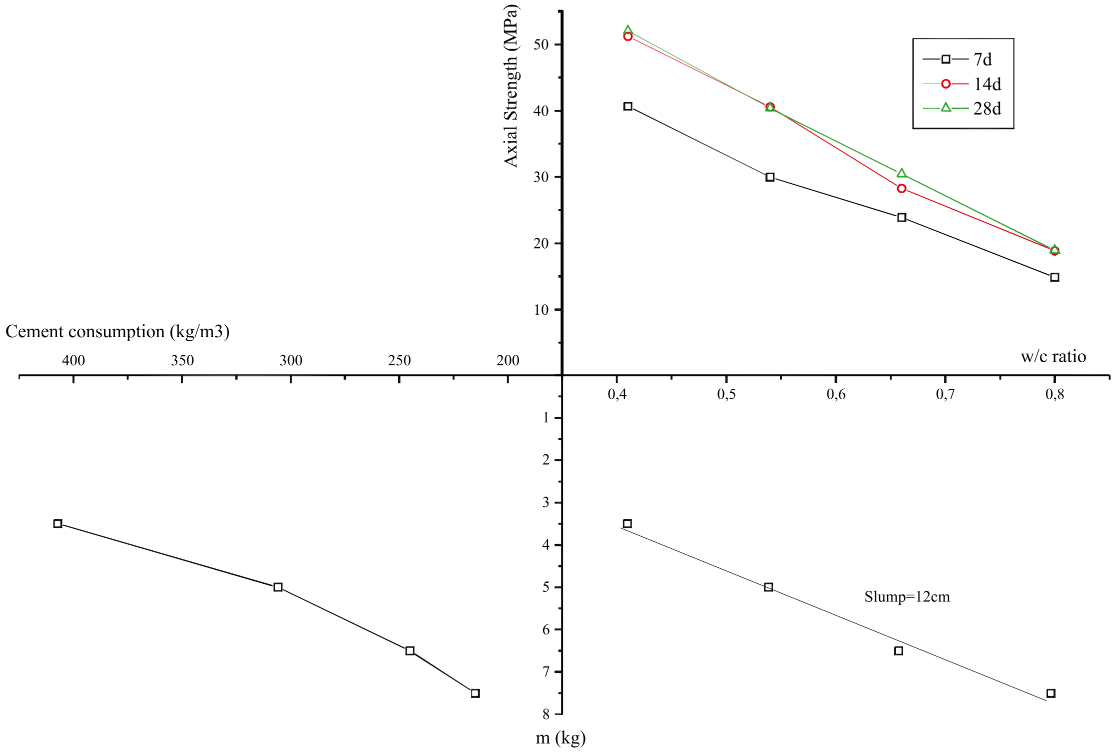


Table 4 – Composition of concrete with w/c ratio equal to 0.46, prepared with natural aggregates

Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Water (kg)
5.952	9.642	15	2.738

Figure 2 – a) Metallic base with same area of the traverse section of the prismatic specimen, where a stainless steel pin was rolled; b) Metallic bases with the pins in the mold; c) Mold fulfilled with concrete

a) b) c)

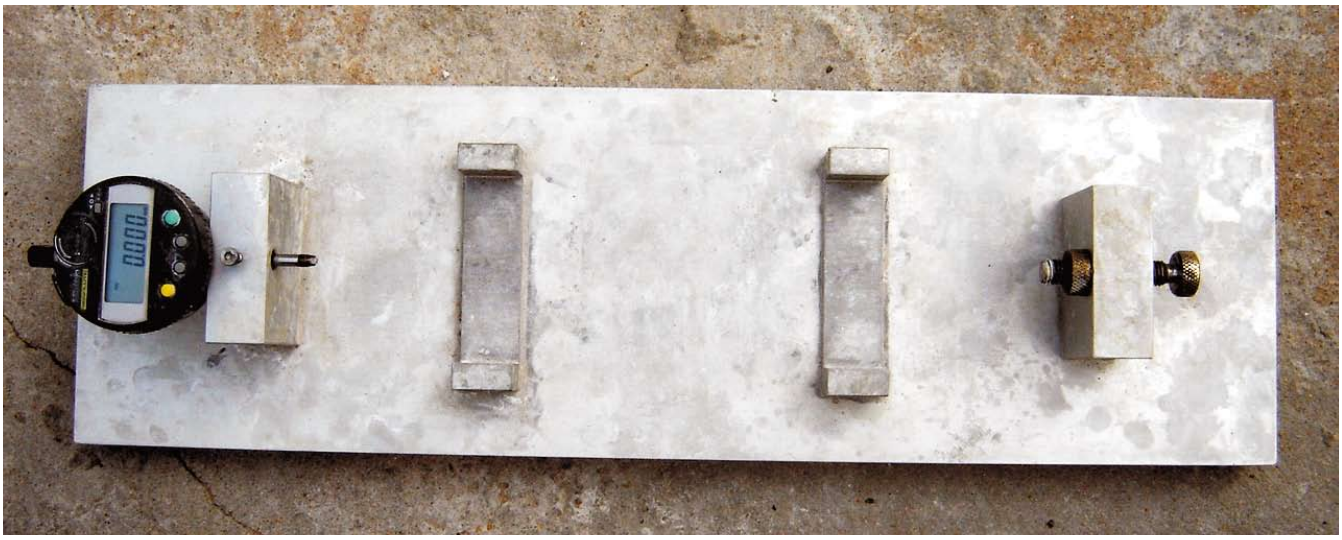
sired workability, fixed at 12±2cm, as indicated by the slump test.

Once the intended workability was reached, two prismatic specimens were molded for each produced mix, according to the procedures of *ASTM C 157-93 – Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*, using wood form. Metallic bases with the same area of the traverse section of the prismatic specimen were used, with a pin of stainless steel in the center. These pins contained grooves in an extremity, to facilitate the adherence to the concrete, and a thread in the other extremity, through which were fastened in the metallic bases (Figure 2-a). Retraction readings were performed considering the distance among those two pins. These metallic bases were put in the wood forms (Figure 2-b), that later were filled with the produced concrete (Figure 2-c). Concrete was compacted in two layers, with application of 25 blows for layer, through a metallic cylindrical baton.

Twenty-four hours after cast, the molds were dismounted. Metallic bases were unrolled showing only a small part of the pin (Figure 3). After that, the specimens were submerged for 30 minutes in containers, holding saturated water with lime, in a chamber with controlled temperature (23±1,7

Figure 3 – Metallic bases were unrolled showing only a small part of the pin

Figure 4 – Metallic apparatus used to measure specimens shrinkage



ºC) and humidity (50±4%). After that period, the specimens were dried with a towel and the initial reading of specimens' length was performed. A metallic apparatus was used, containing a digital deflectometer with a precision of thousandth of millimeter in one of the extremities, in which the specimens were disposed in a horizontal position (Figure 4).

Immediately after the first reading (1 day after molding), specimens were put again in water saturated with lime, where they remain for additional 27 days. Readings at 7, 14, and 28 days after molding, using the same procedure adopted for the initial reading, were performed. After that period, the specimens were disposed in shelves in the same temperature and humidity controlled chamber. Readings at 56, 112, and 224 days were done. It should be point out that the procedure adopted to accomplish the readings was applied at all specimens, maintaining the positioning of the specimens in the measurement apparel during the accomplishment of all readings, to reduce any external interventions, since measured deformations were in the interval of a few thousandth of millimeter.

4. Results

4.1 Initial considerations

As already mentioned, the experimental project involves 7 independent variables and the experiment was fractioned to reduce the total number of specimens to be tested. The treatments were in accordance with a Second Order Composite Design, which enables to test linear and quadratic terms. This design allowed testing linear and non-linear models.

To facilitate model presentation, labels were adopted for the independent variables and response variables, as seen in Table 5. The collected data allows establishing models relating shrinkage with the independent variables, establishing models based on multiple linear regression or non-linear regression.

With the construction of the models, an analysis of the standardized residues was performed. Following standard statistical procedures,

Table 5 – Variable labels used in the model

Símbolo	Variable	
	Name	Type
rmc	Percent of coarse aggreg. substituted for recycled mortar	Independent
rmf	Percent of fine aggreg. substituted for recycled mortar	Independent
rcc	Percent of coarse aggreg. substituted for recycled concrete	Independent
rcf	Percent of fine aggreg. substituted for recycled concrete	Independent
rrcc	Percent of coarse aggreg. substituted for recycled red ceramic	Independent
rrcf	Percent of fine aggreg. substituted for recycled red ceramic	Independent
w/c	water/cement ratio	Independent
ε_{sh}	Shrinkage	Response

$$\varepsilon_{224} = (796.\text{w/c}^{\,0,5}).(1 + 0.232.\text{rcc} + 0.432.\text{rrcc} + 0.351.\text{rmc}).(1 + 0.687.\text{rcf} + \\ + 0.412.\text{rrcf} + 0.567.\text{rmf}) \qquad \textbf{(2)}$$

collected data that generated standardized residuals higher than 3 were eliminated from the analysis. Mixture 3 was in that category.

4.2 Presentation, analysis and discussion of results

Average results of shrinkage obtained for each mixture are presented in Figure 5. It can be observed that all recycled aggregate concretes present shrinkages higher than the reference concrete. Concrete shrinkage of mixture 3 was abnormal and this data was not used in the model building phase.

Shrinkage at 56 and 224 days of age were modeled using multiple regression and significant effects were identified. For the age of 56 days, large variability was observed, impeding the identification of some significant effects. At that age only 4 of the 7 variables were detected as significant and the coefficient of determination was low (R^2=32,5%).

For the age of 224 days, the model still reveals considerable variability, but it was possible to detect all terms as significant. For this age, two models were tested, a linear and a non linear model. For both tests, R^2 was similar, around 42%. This means that the models explain only 42% of the variability observed in shrinkage. Due to its more intuitive nature, the non linear model was chosen to represent shrinkage values, as expressed in the Equation 2.

In that model, the first term represent the effect of water/cement ratio. The second term models the effect of replacement of natural coarse aggregate by recycled coarse aggregate, and the third term represent the effect of replacement of natural fine aggregate by recycled fine aggregate. The percentile of replacement of recycled fine and coarse aggregates should be informed in the scale of 0 (0%) to 1 (100%), while the water/cement ratio is expressed in the usual scale, varying from 0.4 to 0.8. It should be noticed that the sum of the percentile of replacement of natural aggregates by recycled aggregates should be lower or equal to 1 (100%), for each aggregate size (coarse and fine). Equation 2 provides positive shrinkage values multiplied by 10^6. The larger the absolute value found, larger the value of shrinkage presented by the concrete. The attempt of inserting square terms, as ram^2, or interactions, like ram x rag, did not improve the adjustment, therefore these more complex terms were discarded.

The model presented in Equation 2, which describes shrinkage behavior at 224 days of age, was used to generate graphs that illustrate the influence of each recycled aggregate type, for percentages of replacement of 0%, 50% and 100% and water/cement ratio of 0.46, 0.60 and 0.74. These graphs and a corresponding table are showed in Figures 6, 7 and 8 and in Table 6.

As it can be seen in Figures 6 to 8, all recycled concretes presented higher shrinkage than conventional concrete. It was also noticed that water/cement ratio holds large influence on shrinkage. The larger the water/cement ratio, the larger is the shrinkage obtained. According to Table 6, concretes with 0.60 and 0.74 water/cement ratio presented

Figure 5 – Average shrinkage obtained for each mixture

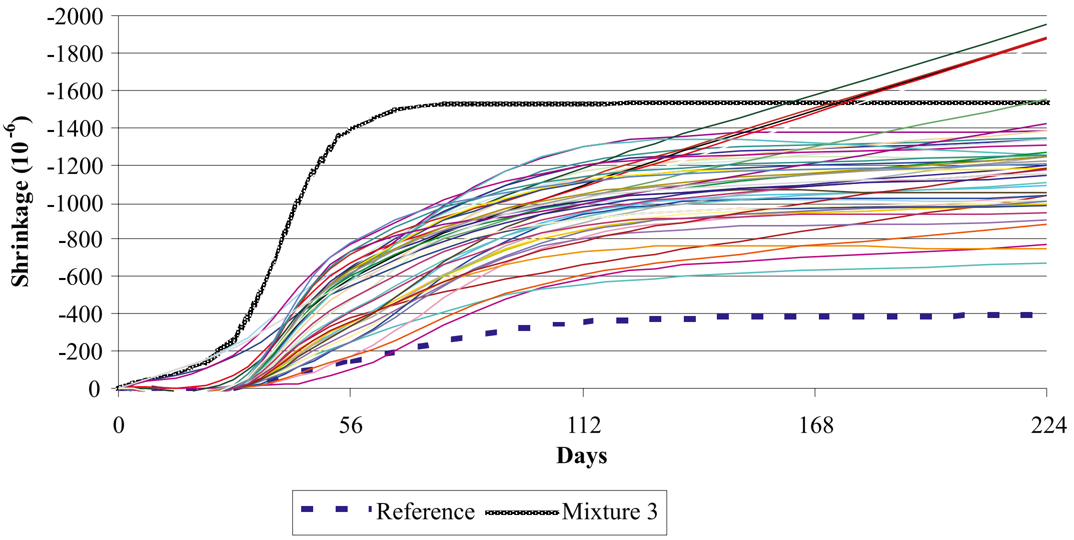
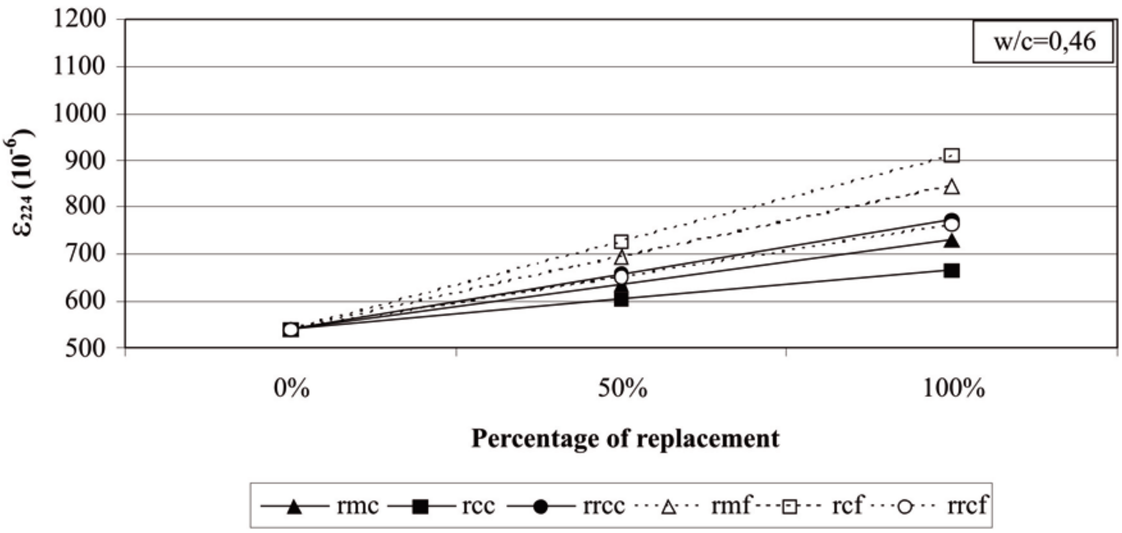


Figure 6 – Shrinkage behavior as a function of percentage of natural aggregate replaced by recycled aggregate, for water/cement ratio equal to 0.46



shrinkages 14% and 27% higher than shrinkage of 0.4 water/cement ratio concrete. That behavior is well established in literature, since concretes with higher water/cement ratio correspond to concretes with a higher content of water, and when that excess of water is lost to the environment, larger shrinkage is experienced by the concrete [26].

In agreement with the model, the continuous replacement of natural aggregates by recycled aggregates, coarse or fine, causes an increment in concrete shrinkage, as reported by other studies [13, 16, 27]. Such effect can be explained due to the higher porosity and lower elastic modulus of recycled aggregates and consequent smaller restriction to deformations of concrete propitiated by recycled aggregates.

Another possible explanation for that phenomenon would be the higher demand for cement paste by those concretes to obtain the same packing degree. Such reasoning is coherent with results pre-

Figure 7 – Shrinkage behavior as a function of percentage of natural aggregate replaced by recycled aggregate, for water/cement ratio equal to 0.60

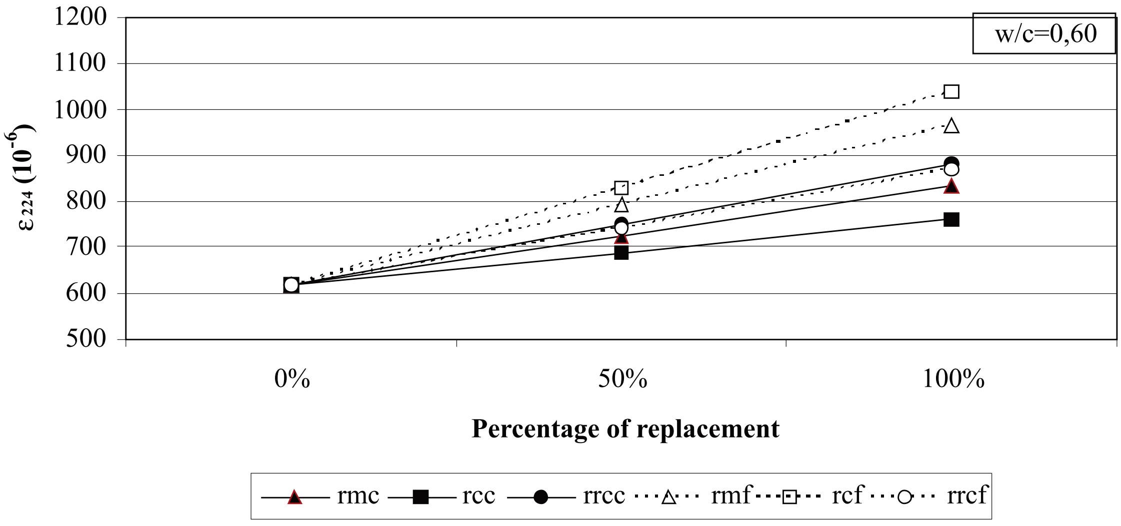
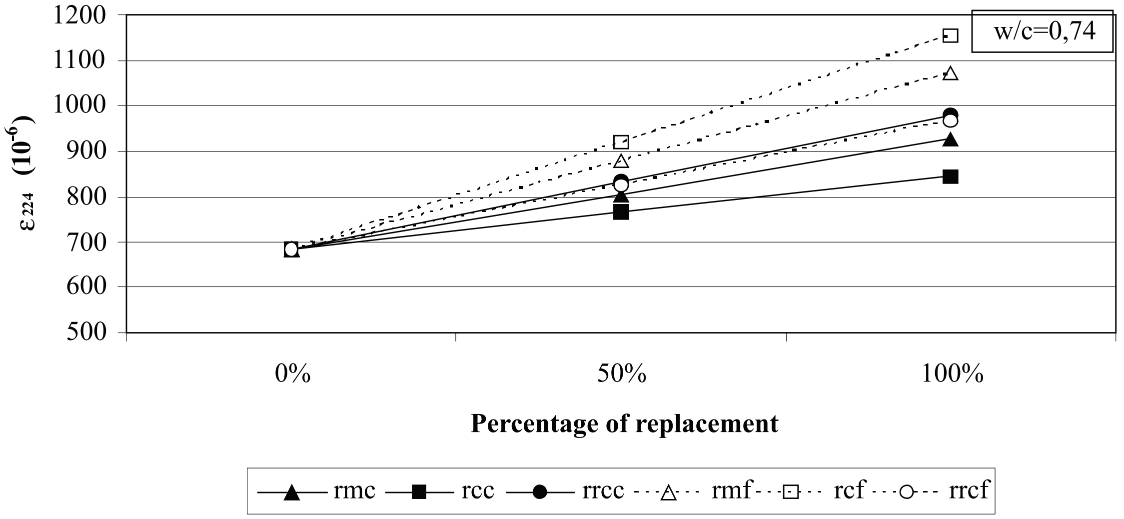


Figure 8 – Shrinkage behavior as a function of percentage of natural aggregate replaced by recycled aggregate, for water/cement ratio equal to 0.74



sented by other author [28], where they verified an increase in cement consumption, and consequently in water content, to maintain the same water/cement ratio. That happens as recycled aggregate content is increased to maintain the specified consistence.

In agreement with the magnitude of the estimated coefficients (Equation 2), ratified by data presented in the Table 6, it is noticed that the fine aggregate replacement produces larger effect on shrinkage than coarse aggregate substitution. The most pronounced effect is associated to rcf (recycled concrete fine aggregate) and the smallest effect, to rcc (recycled concrete coarse aggregate) as can be seen by the magnitude of their coefficients.

According to Table 6 data, considering a substitution of 100%, the use of recycled fine aggregate of red ceramic causes an increment of 41% in the shrinkage. This increment is inferior to the increments propitiated by recycled concrete and recycled mortar fine aggregates, which increase the shrinkage by 69% and 57%, respectively, when they totally replace the natural fine aggregates. However, the increments in shrinkage propitiated by 100% replacement of natural coarse aggregates by recycled concrete, mortar and red ceramic coarse aggregates are around 23%, 35% and 43%, respectively.

5. Conclusions

According to obtained results, concretes produced with recycled aggregate present larger shrinkage than reference concrete. For the age of 56 days, excessive variability was observed in shrinkage concrete results, and only 4 of the 7 independent variables were detected as significant terms. For the age of 224 days, shrinkage results still reveals large variability, however the significant effect of all tested factors was detected. According to the experimental study, the most pronounced effect is associated to the use of recycled concrete fine aggregate (rcf) and the smallest effect to the use of recycled concrete coarse aggregate (rcc).

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